A RAM based digital pattern generator for scanning Auger microscopy.

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Abstract

The design of a digital raster system used with a computer controlled scanning Auger microscope has been simplified by using a pattern generator based on a fast random access memory. The pattern generator allows a variety of scan formats and modes of operation that are necessary for the operation of a combined SAM/SEM system.

1. Introduction

Scanning Auger microscopy (SAM) has become very dependent on computer techniques for data acquisition and results presentation, (Prutton and Peacock 1982) and several groups have used dedicated micro and minicomputers for control of these instruments (e.g. Bishop 1980, Frank and Vasina 1980, Browning et al. 1982). A major element required in the computer/microscope interface is an image raster generator. The raster is needed for regular scanning electron microscopy (SEM) and for display of Auger images. It is possible to generate a scanning raster by using digital to analog (D/A) converters directly from computer digital ports, but although simple, this is not a good option for line and frame scan generation. The smaller mini computers often used for controlling Auger microscopes are relatively slow compared with conventional rastering electronics, and they are also not synchronous devices, which is a requirement for photographic output. Further the computer is unable to manipulate data and simultaneously output a scan for SEM display. The purpose of this paper is to describe a digital raster generator that largely frees the computer from active control and meets the requirements for synchronous operations.

A digital pattern generator was chosen as the basis of the raster scan electronics. The pattern being the picture element (pixel) positions in the array that forms the digitally scanned image. The raster scan being fully digital has the advantage that, unlike a mixture of analog and digital scans, only one raster system is needed for SEM viewing, Auger imaging, and digital image output. A direct 1:1 correspondence of SEM and Auger data can be obtained with a single digital raster system, and as SEM data can be annotated from software, collection and interpretation of results is made simpler.

There are two approaches to designing a digital pattern generator for raster scan. Either a dedicated TTL logic unit could be built, or a separate stand alone microprocessor board used. The disadvantage of the first approach is that of designing a flexible system that is the simplest solution, given the difficulties of building and testing such equipment. The disadvantages of using a dedicated board level computer are that it is still relatively slow, and the true machine code programming task is considerable. In computerizing the Auger microscope described by Todd et al. 1979, the output of a fast raster was considered to be important in viewing, not only the regular SEM image, but also

Auger images stored in the computer memory. Therefore a dedicated TTL logic unit was designed to accomplish this. To simplify the design, much of the pattern generation is actually done by a computer and then output by the pattern 'generator' from its own internal memory.

The pattern generator was designed to facilitate a variety of operations as set out in table 1. The several data types, and the need to set up several formats for imaging, requires that the pattern generator be more than a fixed X,Y scan generator. Flexibility has been obtained by using data from a 2K by 16 bit random access memory (RAM) for the scanning X pixel position. The logic has been simplified by using a 16 bit control register for accessing the RAM, and controlling the output functions. Only the X pixel data (line scan) has been included in the RAM, as the Y data (frame scan) can be generated by, and output from, the computer without compromising speed of operation. Also for regular SEM viewing a simple Y scan is sufficient and a counter has been used for this.

2. Theory of operation

The pattern generator was designed to be a computer controlled peripheral operated by two 16 bit buses. In the author's case these buses are derived from a Hewlett Packard HP9845B desktop minicomputer through two general purpose I/O ports (HP98032A). One of these 16 bit buses is used for a data bus and the other an address bus. The address and data buses also control the I/O registers to the microscope and Auger sub-systems (see Figure 1). The circuit diagram for the pattern generator is shown in Figure 2.

The pattern generator is based on a 2K by 16 bit RAM which is filled with X pixel (line) data generated by the HP9845B computer. This X pixel information is then clocked out independent of the computer to generate line and frame scans. Only 12 bits of the RAM word are used as X pixel data, the other 4 bits are used for blanking of the SEM displays and control of the counters. It is this approach, of using the computer to generate the X pixel data and control bits, that in relative terms simplifies the logical design of the pattern generator. The X pixel output of the RAM is also very flexible in format. The X pixel positions can be arbitrarily set by the compu ter and several modes of operation can be derived

from the three control bits. The 2K RAM is divided into two separately addressable blocks of 1K x 16 bits. Two different formats of up to 1026 points per line can then be stored at any one time.

Two different methods of generating the Y scan (frame) are used. The 12 bit Y scan data can either be output directly from the computer on to a data storage latch, or an 8 bit counter can be used for generating a 256 line per frame raster. The 256 line raster is used for regular fast SEM viewing and using an independent counter frees the computer from any need for active control after setup. The RAM contains the blanking and increment control for the Y counter. This means that more than one Y increment instruction per line can be contained in the RAM. A choice of formats of 256/n equally spaced lines per frame can therefore be programmed in.

The outputs of the RAM and the X data latch, as well as the 8 bit counter and the Y data latch, are tri state. These are connected directly to the respective 12 bit D/A inputs. The choice of which outputs are enabled is made by the computer and set in the pattern generators control register. All of the output ports X, Y and Z (blanking and image intensity) can thus be controlled independently by the computer for tasks such as cursor generation and

point data collection.

2.1 Clocks

The timing of the pattern generator is synchronous and separate from the computer operations. The timing is generated by a 5 MHz crystal controlled oscillator counted down by an 8 bit variable divide by n counter to produce a variable clock. The clock period is computer controlled by setting an 8 bit word onto a latch. This word is loaded into the counter when the counter carry out, $\overline{CO}$, is true. This variable clock controls both the sampling period, for collection of experimental data, as well as the rastering speed of the pattern generator.

2.2 Sampling modes

There are two modes of Auger data collection. In the first mode a sample area is scanned, and the frame scan time is used as the data acquisition time for electron counting and voltage to frequency conversion. In the second mode a single X and Y position is output, using the X, Y latches, and the data acquisition time is a multiple of the variable clock period. Two different counters are used for these operations. For area scan, the RAM is addressed by a 10 bit counter, with single frame conditions set on the control register. For single point data acquisition, a 16 bit counter is used to scale the

variable clock. Both modes are started by setting a flip-flop, which is reset at the end of the sampling period. The state of the start/stop flip-flop appears as bit 14 of the status register.

2.3 Control word

The logical design of the pattern generator is simplified by using a 16 bit control word register. This register is addressed by the computer and contains the information that enables the tri state outputs of the RAM and X,Y latches. The control word also contains the write enable and chip strobes for operating the RAM, and contains other logical flags. Table 2 gives a list of the operations. Most of the logical decisions in operating the pattern generator are therefore made by the computers software. Except for the TTL logic necessary to protect the tri state outputs, and the need for an asynchronous interface with the computer, little other logic is required.

2.4 Computer interface timing

The asynchronous interface with the computer is on the data bus. The address and data buses derived from the HP98032A I/O ports have a two line handshake that must be satisfied. The initiating line, peripheral control (PCTL), is set by the computer which is the bus master. This line is then reset after the second line, the return peripheral flag (PFLG), is set. A new handshake can be initiated

when PFLG is cleared by the peripheral. The 16 bit bus used for register addressing in the pattern generator has these two lines linked so that no peripheral delay is introduced. The 16 bit data bus handshake interacts with the pattern generator in two ways. Firstly, the handshake is synchronized with the pattern generator's variable internal clock. Secondly, the synchronized handshake can be used as the clock for operating the RAM address 10 bit counter. This allows the computer to clock through the RAM, and enter data into the RAM through the X latch. This loading operation is controlled by the control register. Using the synchronous handshake as the RAM clock also allows the computer to output images from memory. The computer can output to the CRT displays using fast direct memory access (DMA) while the pattern generator scans a line or frame. For this the control register has set a fast Z latch enable, FZE, which loads the Z latch with computer output data as the 10 bit counter is clocked on with the DMA handshake. A fast image display of the computer memory is thus effected.

2.5 RAM control bits DX12-DX15

The different functions, single line, and free running line, blanking and Y counter increment are controlled from the contents of the RAM. DX12 and DX13 are used as 'stop count' and 'reset counters'

flags, and are active low. For continuously running line and frame scans DX12, stop count, is set by the computer to be high at the end of a line, with only DX13, reset counters, low. The line scan 10 bit counter is then reset to the lowest RAM address when DX13 is low, but continues to count, outputing the next line. A variable line flyback time can be generated by setting the blanking low, and outputing the first X position to the D/A on several RAM addresses before reset counters low is reached. The Y counter increment is normally output one address before the reset, but can be anywhere in the flyback. The flag FEI, frame end inhibit, on the control register, determines whether a continuous frame or a single frame is output. This flag inhibits the carry out, $\overline{CO}$, on the 8 bit Y counter which would reset the start/stop flip-flop at the end of a frame.

2.6 Operations

The combination of single point, single line, single frame, free running line and free running frame, taken with a variable clock and image format, is sufficient for all the operations listed in table 1. The computer can be freed for other tasks during acquisition or SEM rastering, and during operation will normally only start the counting and monitor the stop flag on the status register.

Timing diagrams and further details of operation are available from the author.

3. Results

The computer controlled pattern generator is used with the microscope described by Todd et al. 1979. This is an electrostatically scanned field emission microscope that is integral to a concentric cylindrical mirror analyzer. The operation of the pattern generator is controlled partly through the use of menus displayed on the HP9845B graphics display, and partly by using the eight programmable 'softkeys' on the graphics CRT hood. These softkeys can be labled by using the lower region of the graphics display. Magnification, sweep speed, cursor position, photographic output, and other funtions are controlled from these keys which use end of line branching from the main program. This allows some interactive control of the SEM while other tasks are in progress.

An important feature of the pattern generator is the correspondence of SEM and Auger data. Figure 3 shows reference SEM output for Auger line scan applications. The micrograph is output on a Tektronics 602A display with 800 lines resolution. The raster is 1020x1020 pixels with a highlighted cursor showing the sampling positions. The end points are set us interactively, and displayed with a 512x512 resolution overlaying the normal 256x256 fast

scan SEM. Due to the sweep delay in the SEM scan electronics, the actual end points are displaced from the positions used for Auger data collection, 20% of a line scan at the highest sweep rates. A slow scan photographic sweep with a cursor is therefore important for interpretation of the data. From a reference SEM such as figure 3, an accurate measurement of feature positions can be made, and related to the corresponding Auger linescan. There is a similar requirement for point and multiple point Auger spectroscopy.

The pattern generator has the ability to control the output of data from the computer memory for interactive viewing, without the need for a dedicated image frame store. Because of the relatively long acquisition times needed for the creation of Auger images, $\sim 10^{3}$ seconds, (Browning et al. 1977) the number of pixels in an image is normally lower than that used for SEM imaging. The computer memory requirements are therefore modest, needing only 16K bytes per electron energy imaged. A 128x128 image can be output at a 10Hz repetition rate, this is limited by the HP98032A interface speed, and is normally displayed on a slow phosphor Tektronics 401 display for interactive viewing. The contrast and black level are controlled by a softkey menu.

As the image format is quite flexible, images can be displayed on alternatives to a square pixel grid. A 128x128 image based on a hexagonal grid, six equal distance nearest neighbors, can be formed by loading one address block of the RAM with two offset lines, and incrementing the 8 bit Y counter, with flyback and blanking, four times for each scan of the RAM. Figure 4b shows a hexagonally scanned Auger image with a SEM reference Figure 4a. The Auger image is from the carbon KLL transition and each pixel has been 'filled' out to a hexagon for photography. The SEM shows a section of a tungsten cored SiC fiber.

4. Conclusion

The concept of using a RAM based pattern generator for rastering an Auger microscope, has proved very effective. As fast TTL compatible RAM is becoming lower priced, it is quite cost effective to replace TTL logic with computer programmable logic for special function interface boards.

The pattern generator described here has been used for most of the operations routinely used in scanning Auger microscopy, and has been found to be a flexible and convenient solution, that will also enable novel imaging techniques to be tried.

Acknowledgements

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Tables.

Table 1. Scan operations needed for a SEM/Auger microscope.

Table 2. Control word operations.

Figure Captions

Fig. 1 System diagram for SAM control electronics.

Fig. 2 Circuit diagram of RAM based pattern generator.

Fig. 3 1020x1020 pixel reference SEM for Auger line scans.

Fig. 4a Reference SEM for Auger image 4b. Section of a tungsten cored SiC fibre.

Fig. 4b Carbon Auger image, 128x128 pixels on a hexagonal grid.

Table 1

Scan operations needed for a SEM/Auger microscope.

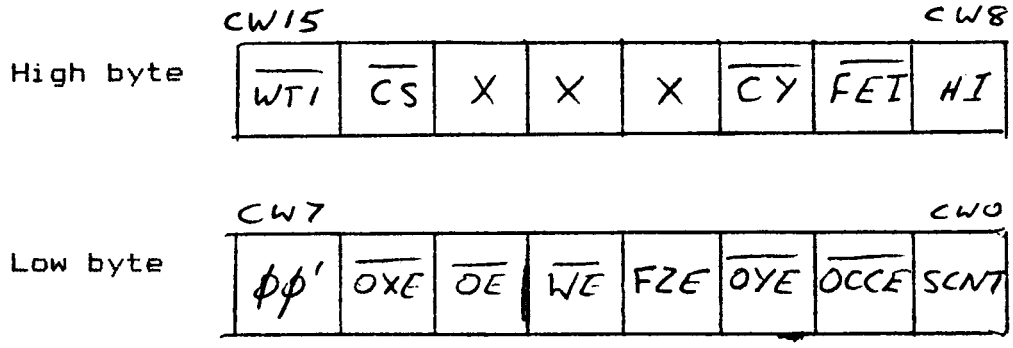
Auger spectroscopy	Single point sampling
	Area scanning sampling
	Variable acquisition time
	Interactive cursor
Auger line scans	Rotatable vector
	Variable step and line length
	Variable acquisition time
	Double interactive cursor
Auger images	Variable number of pixels
	Format for intensity display, (Z mod)
	Format for Y axis display, (Y mod)
	Variable acquisition time
SEM viewing	Variable number of pixels
	Variable scan speed
	Free running frame
	Free running line
	Interactive cursor

SEM photography	High resolution slow scan
	Optional cursors and annotation
	Single or multiple frames
Data output**	Interactive image display
	Photographic image recording

** Most data output is on a graphics display and plotter.

Table 2

Control word operations



CW0 Set counters to 1's, SCNT

CW1 (RAM scan) OR (Time scaler) output enable, $\overline{OCCE}$

CW2 (Y latch) OR (Y counter) output enable, $\overline{OYE}$

CW3 Fast pixel intensity loading enable, FZE

CW4 RAM write enable, $\overline{WE}$

CW5 RAM output enable, $\overline{OE}$

CW6 X latch output enable, $\overline{OXE}$

CW7 Raster clock choice, φφ'

CW8 RAM high address block, HI

CW9 Inhibit STOP from frame end, $\overline{\text{FEI}}$

CW10 Clear Y counter, $\overline{\text{CY}}$

CW11 - CW13 NOP , X

CW14 RAM chip select, $\overline{\text{CS}}$

CW15 Logic inhibit for RAM loading, $\overline{\text{WTI}}$

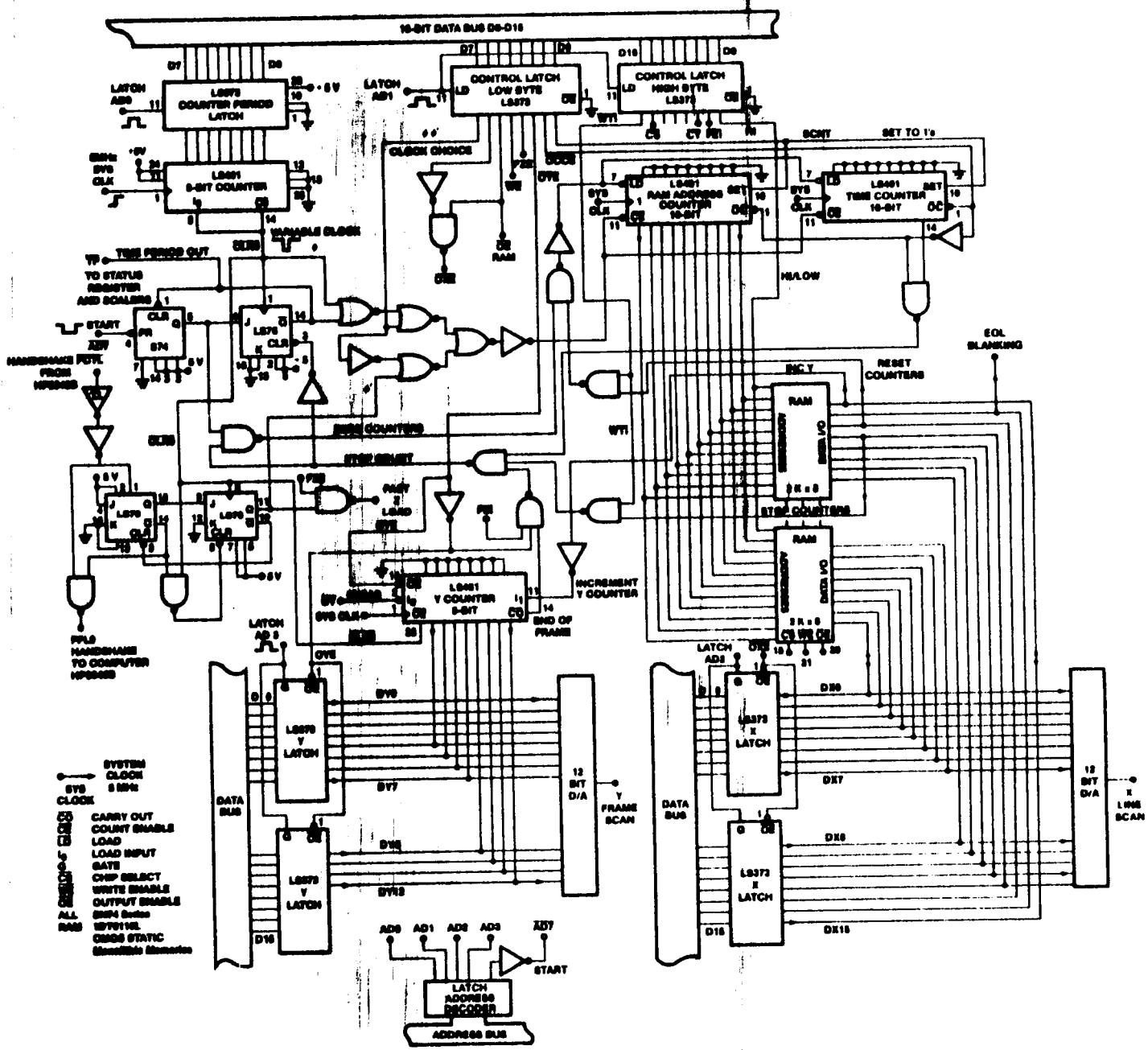

16-BIT DATA BUS D0-D15
CONTROL LATCH LOW BYTE LS373
CONTROL LATCH HIGH BYTE LS373
LS670 COUNTER PERIOD LATCH
LS491 16-BIT COUNTER
LS491 RAS ADDRESS COUNTER 16-BIT
LS491 TIME COUNTER 16-BIT
LS491 Y COUNTER 9-BIT
VARIABLE CLOCK
TIME PERIOD OUT
TO STATUS REGISTER AND SCALERS
START
HANDSHAKE FROM HP9845
HANDSHAKE TO COMPUTER HP9845
RESET COUNTERS
EOL BLANKING
INCREMENT Y COUNTER
END OF FRAME
RAM
LS670 Y LATCH
LS373 X LATCH
12 BIT D/A
Y FRAME SCAN
X LINE SCAN
DATA BUS
LATCH ADDRESS DECODER
ADDRESS BUS
SYSTEM CLOCK 8 MHz
CARRY OUT
COUNT ENABLE
LOAD
LOAD INPUT
GATE
CHIP SELECT
WRITE ENABLE
OUTPUT ENABLE
CMOS STATIC

FIGURE 2.

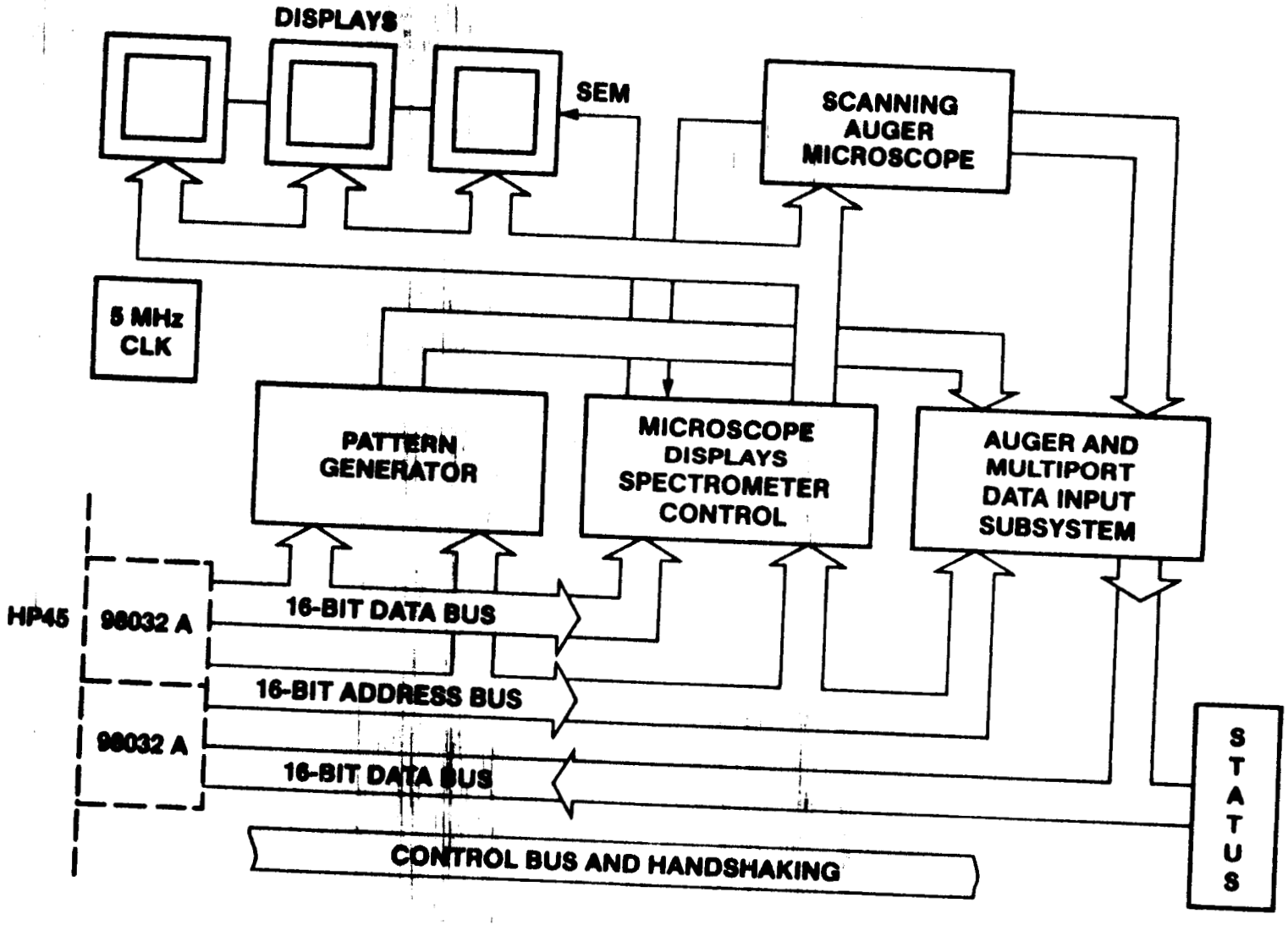
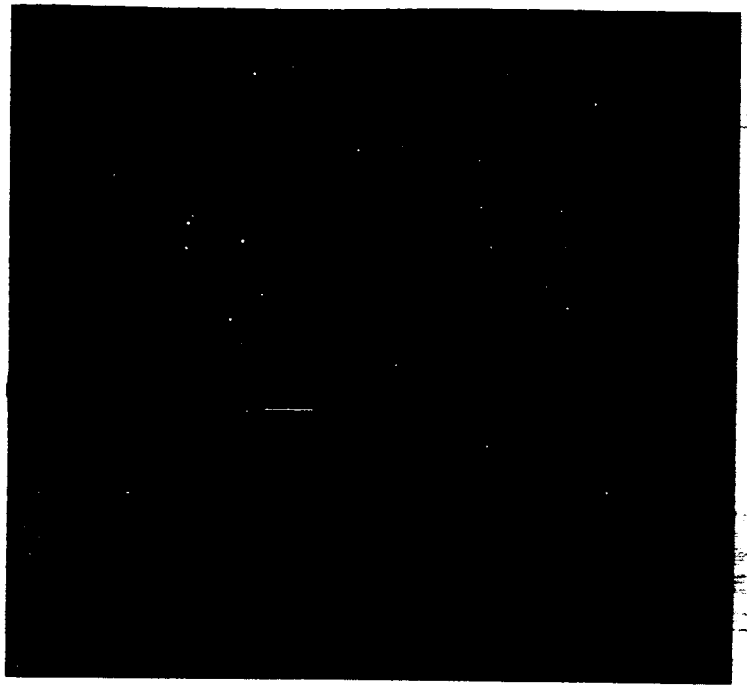
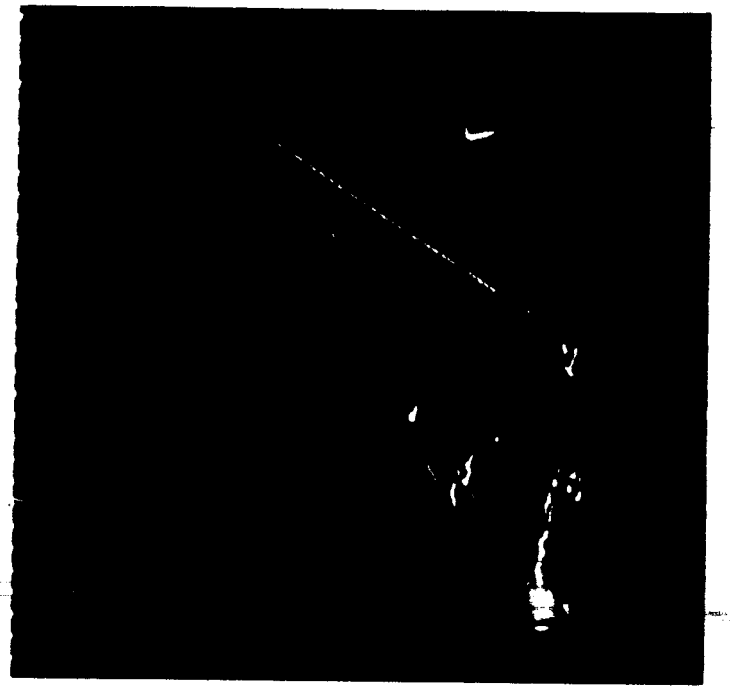
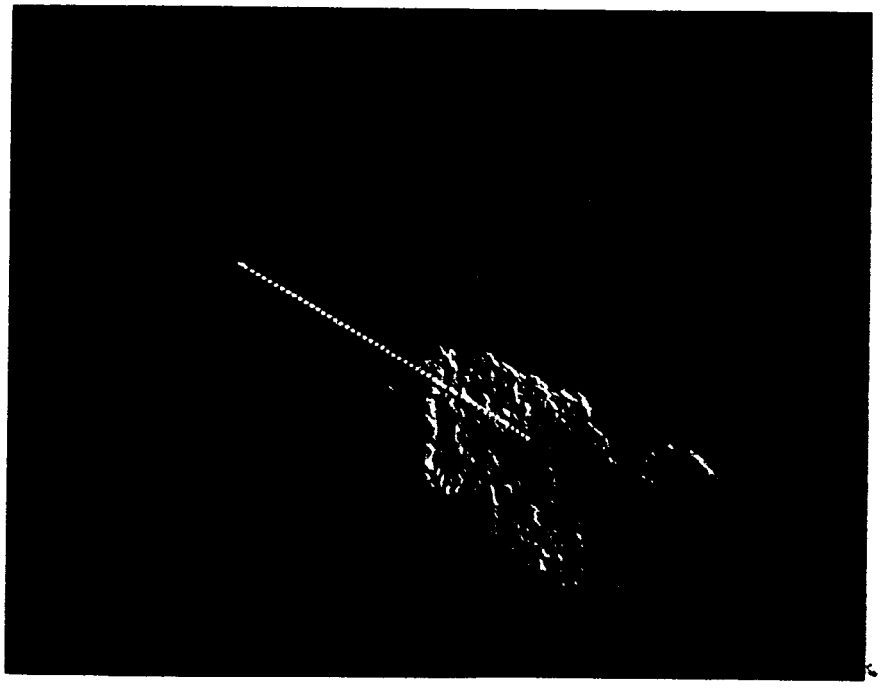

DISPLAYS
SEM
SCANNING AUGER MICROSCOPE
5 MHz CLK
PATTERN GENERATOR
MICROSCOPE DISPLAYS SPECTROMETER CONTROL
AUGER AND MULTIPORT DATA INPUT SUBSYSTEM
HP45
98032 A
16-BIT DATA BUS
16-BIT ADDRESS BUS
98032 A
16-BIT DATA BUS
CONTROL BUS AND HANDSHAKING
STATUS

Figure 1.







Ref 2.

SCANNING ELECTRON MICROSCOPY/1983/IV (Pages 1655-1663)
SEM Inc., AMF O'Hare (Chicago), IL 60666 USA

INTERFACING AND COMPUTER CONTROL FOR SURFACE SCIENCE MICROSCOPY

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Abstract

Computerized instrumentation is playing an increasingly important part in the development of Auger microscopy. The problem of interpreting Auger data is seen as an area where computer methods are particularly relevant and considerable progress is being made. Many of the problems associated with Auger microscopy are related to those of quantitative Auger spectroscopy and consideration of these may provide insight for novel microscopic techniques. With the varied problems, methods and data types in Auger microscopy, large and sophisticated computer programs are necessary. The creation of these programs is a major task in implementing a computerized system as there is little existing software that is available and readily portable.

KEY WORDS: Auger, Microscope, Microprobe Computer, Software, Scanning Auger Microscope, Data System, Topography, Noise, Quantitative.

Introduction

With the advent of powerful, yet cheap, microprocessors, computer control and data acquisition have become almost an obligatory part of the instrumentation in many fields of physics. Surface physics similarly has moved towards digital techniques not only for control and acquisition but also to use the computing power for data reduction and presentation. Computers are used to improve accuracy, to expand the data set and to increase the rate of information flow. However, in surface microscopy and in particular scanning Auger microscopy, the computer is not just a convenient data processor, it has become an integral part of the apparatus and technique. This has not always been true. Although MacDonald (1970) began with a computer controlled instrument, most of the initial experiments and instruments were not computer controlled. This, in retrospect, is not surprising. The technologies of the U.H.V. surface microscope, and in particular those with high brightness electron sources, were novel and difficult to use without the added complication and expense of computerization. Furthermore, a priori, it was not really appreciated how little information about surface stoichiometry was contained in a raw Auger micrograph, Ono et al. (1974). As higher spatial resolution became available, it was found that the surface topography of a sample dominated, producing a confusing and misleading image that needed subjective interpretation, Seah and Hondros (1973), Powell et al. (1975), Venables et al. (1976), Todd et al. (1979). Indeed, some ingenuity was needed to find an elemental system in which the latent power of the imaging technique could be clearly demonstrated, Janssen and Venables (1977). It became more normal to use fine point electron spectrometry for analysis with self-consistent normalization of Auger intensities. Auger micrographs could then be used for initial surveys, line scans for semi-quantitative analysis, and point spectrometry for quantitative analysis. The large information content of an image was relatively untapped because of the problem

of separating out the contrast mechanisms. With the discovery of Janssen et al. (1977) that much of the topographic variation in Auger yield could be normalized by using the similar variation of the background electrons under the peak, Auger micrographs from rough surfaces became more meaningful. The use of this normalization scheme gives good qualitative results on many samples, but care must be taken to interpret the image as 10%-30% intensity variations may well be topographic. Other contrast mechanisms present are chemical shifts, backscattering variations from the bulk, and accumulation of charge on oxides. The Auger image can thus be very complex, and it is partly for this reason that computerization of the image collection is so necessary.

In this paper we will review some of these contrast mechanisms and other characteristics of the data from an Auger microprobe. We will also review some of the varied techniques for which computers have been used in Auger microprobe analysis. Not all Auger microprobes have been computerized for image processing, and it has by no means been demonstrated that Auger imaging is a routine technique for materials characterization, Prutton (1982). More emphasis has been recently put on computing techniques for quantitative analysis from spectra. The utility of computer methods for characterizing the spectrometer response, and thus in accurately comparing spectra with standards, has been clearly demonstrated, Strausser et al. (1981). However, for rough and complex surfaces where Auger microprobe images cannot be quantified, then some inaccuracy must persist in the analysis of spectra. To exploit fully the power of the Auger microprobe on such surfaces, line scans and imaging must play an important part. The computerization of an Auger microprobe must therefore be sufficiently flexible to not only use present quantitative analysis methods, but also to be able to incorporate new analytical methods.

Techniques and Applications

Taylor et al. (1977) showed the utility of computer data processing to reduce topographic effects on Auger images. First, they collected a line scan at the energy of the Auger peak and then a line scan at an energy in the background. By subtracting the two line scans and normalizing the difference, the topographic contrast was reduced. An Auger image could then be built-up photographically line by line. They also demonstrated some other features of computerized acquisition, viz. interactive graphics, results presentation, and data manipulation. Keenan and McGuire (1977) had previously noted the advantage of interactive graphics for Auger data reduction, in allowing a variety of techniques to be tested and compared. They also pointed out the problems of creating a data glut from the much more rapid acquisition of raw data, to which can be added the 'new' data generated by the computer. Both Taylor et al. (1977) and Keenan and McGuire (1977) used the analogue output from the spectrometer system. They then digitized using a voltage-to-frequency (V/F) converter, and an analogue-to-digital (A/D) converter, respectively. With the low beam currents used in high resolution microscopy, this is not an ideal method. Microprobe Auger signals are many orders of magnitude lower than with regular Auger spectroscopy, even with high brightness electron sources, Powell et al. (1975), Gerlach and MacDonald (1976), Venables et al. (1976), Bishop (1977), Browning et al. (1977), Todd et al. (1979), Todokoro et al. (1981). It is important, therefore to maximize the efficiency of detection. One method to do this is to use an unmodulated spectrometer with electron pulse counting, MacDonald (1971), Prutton (1977). This leads naturally to treatment by digital methods, both in subtracting counts for Auger imaging and also for generating rasters and energy scans, Staib and Staudenmaier (1977), Browning et al. (1977), Shimizu et al. (1977).

The use of LaB_6 and field emission high brightness cathodes is a further reason for needing data reduction. These sources can be unstable with large fluctuations of beam current, Christou (1976), Nakagawa (1978). The effects are most severe for field emission sources, and, if N(E) data is required, some form of normalization against beam current is needed. Bishop (1977) used sample current, Browning et al. (1977) the SEM signal, Zironi and Poppa (1981) an internal anode current from the microscope column. For Auger mapping and dN(E)/dE spectra the background normalization can be used to compensate for the flicker noise, Janssen et al. (1977).

The computer hardware used on Auger microprobes has been quite varied. Strausser et al. (1981) and Keenan and McGuire (1977) used minicomputers, with quite simple interfaces to the microscope and analyzer. Bishop (1980) and Browning et al. (1981) used desk top microcomputers, with Bishop using a separate dedicated microprocessor, and Browning et al. complex logic and counters, for input/output. Frank and Vasina (1979), and Gerlach and MacDonald (1976) used board-level microcomputers controlled from an instrument type front panel, with 'built-in'functions, for operator utility. The aims of computerization and the software are equally varied. Strausser et al. (1981) have concentrated on powerful data reduction for quantitative analysis from N(E) spectra during sputter profiling. They have used the Sickafus (1977a,b) linearized cascade for background modeling, subtraction of standard spectra for quantifying overlapping features, and analysis of loss tails to look at near surface heterogeneity. Keenan and McGuire (1977), Shaffner and Keenan (1979) and Shaffner (1980) have used dN(E)/dE for both Auger mapping and spectra. They have concentrated on rapid semiquantitative analysis and image processing. Bishop (1980) and Browning et al. (1981), both using higher spatial resolution probes, $<$ 50nm, and field emission sources, had suppression of topographic contrast and the flicker noise as immediate aims.

In the last few years there has only been a handful of laboratories that have computerized "in-house" an Auger microprobe, as an alternative to buying a commercial product. As the available commercial instruments improve in spatial resolution and software, it is becoming more and more attractive to buy a system rather than the elements to construct and build a system. In many ways this is inevitable and could be compared with the similar situation with regards to regular SEM instrumentation. However, there is a problem with Auger microscopy related to the necessary computerization, and nearly complete control, of these instruments. Commercial software is often not readily accessible to the user thus obstructing any change in the technique desired by the researcher. This hands-off approach by manufacturers is in reaction to the complexity of the software, and the manufacturers need to service and maintain the software and hardware systems. The role computerization will play in a single research instrument will be inevitably more limited, at least initially. It would then be appropriate to implement a forward looking computer system with the capability of modifications as the methodology is improved. Consideration of the signal characteristics of an Auger microprobe, and the possible data reduction techniques, is necessary in order to do this.

Signal Characteristics

The detected Auger signal from a surface is low level and very complex. Effects due to surface topography, the sample matrix, shot noise and very often flicker noise are some of the major causes of difficulty in extracting information about the surface.

Surface Topography

The effects of surface topography on the Auger signal from a pure elemental sample come from several mechanisms. The most marked effects are due to (a)changes in primary excitation with incident angle, (b)emission anisotropies, and (c)detection effects.

(a) As the primary beam angle of incidence varies away from the surface normal, the sampling volume increases as Sec θ until the range of the incident electrons comes within the escape depth of the Auger electrons. This is generally observed, but other processes lead to more complex dependencies, Holloway (1975), Allie et al. (1974).

(b) The diffraction of Auger electrons and angular anisotropies in the Auger process will give apparent yield variations with either topography or crystal grain orientations, Aberdam et al. (1977), Zehner et al. (1976).

(c) The detection of Auger electrons from a rough surface will be influenced by several possible effects. Besides the change in inclination angle of the detector to the surface, which will sample the variations in emission, there are the effects of shadowing. The detector can either be shadowed by the surface itself or by obstruction of the detector by nearby raised surfaces, Prutton et al. (1983).

Other topographical contrast mechanisms include edge effects, Shimizu et al. (1978), and variations in sub-probe size microroughness, Holloway (1975).

Several methods have been published that reduce the effects of surface topography on Auger micrographs, Seah and Lea (1973), Janssen et al. (1977). The majority of schemes are based on the similar topographic correspondence of the background and Auger signals. The background normalization methods were originally used with analog lock-in detection and a modulated spectrometer, but they are now more commonly used with electron pulse counting and energy switching. The method is illustrated in Fig. 1. The height of the Auger peak is measured by counting on the Auger peak (count N_1) and then on the background above the peak (count N_2). The Auger signal intensity is represented by the difference, N_1-N_2. The Auger signal is then ratioed either by the background count N_2 or by $(N_1 + N_2)$ which represents more closely the analogue method used by Jannsen et al. (1977). These schemes have been compared by Prutton et al. (1983) who found that while the normalization $(N_1 - N_2)/(N_1 + N_2)$ gave less intensity variation with topography, the nonlinearity of this scheme would distort the measurement of larger Auger peaks. They also reported that the absorption current on some single element samples was monotonic with incident angle and used this very effectively in a correction to the $(N_1 - N_2)/(N_1 + N_2)$ scheme. This is using a measure of the surface angle as a correction, but it is limited in application, as the secondary electron coefficient will also vary with surface composition on more complicated surfaces. This led them to propose measuring the surface angle by using two backscattering detectors and a similar correction. Lebiedzik et al. (1979) have published a method using a quadrant backscattered electron detector for measurement of surface angle that might be used in this context. The advantage

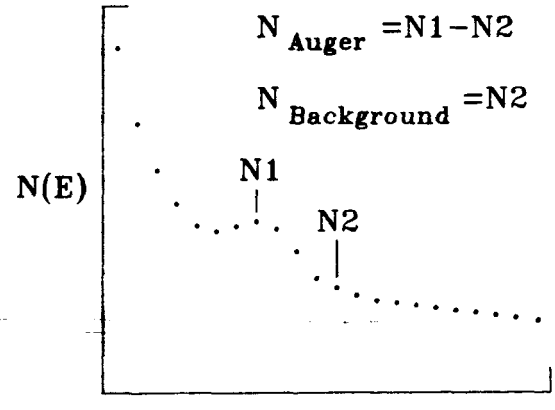

Fig 1
Illustration of the Auger signal used for imaging.

of measuring the instantaneous angle would be enormous. For not only could a correction factor be calculated, but also a morphological surface profile. There will be limits to the technique, in that positioning of the detectors will limit the measurable angular range, and the correction curve will not be expected to be constant for large changes in stoichiometry.

Since Seah and Lea (1973) published their colour normalization technique, it has been used very little. Self-consistent normalization of multiple Auger intensities is well established for quantitative spectrometry but is problematical for Auger mapping. The requirements demand a large computer memory and a very stable sample stage for the long data acquisition times needed. The latter is true if a 1:1 comparison with SEM images is needed for techniques such as false colour presentations. The technique may well be a viable alternative now that 1 Mbyte memories are available in small computer systems, as not only several Auger intensities per pixel may be stored, but also a higher resolution SEM image can be collected simultaneously. The colour normalization method may well prove to be valuable on very rough surfaces and also surfaces with some voltage contrast as a small amount of charging will produce a similar effect on all peaks if N(E) detection is used.

Beam Current Flicker Noise

In order to maximize the Auger count rates, while reducing the electron probe size, many surface physics microscopes use high brightness cathodes such as LaB_6 or field emission sources. These sources can be considerably noisier than tungsten thermionic cathodes, Nakagawa (1978). Electron probes from field emission sources, in particular, have a strong flicker noise content. The form of the flicker noise is dependent on the type of field emitter. For example the current from tungsten (310) cold field emission tips in general, decays by steps over a period of minutes or hours depending on the vacuum and extraction conditions. The emission is then recovered by high temperature flashing, Browning et al. (1977), Bishop (1977), Todokoro et al. (1981). For thermally assisted tungsten (100) emission sources the average current is constant for very long periods but the flicker noise content is of a higher frequency, typically 0.1 Hz to 10 KHz with 5%-10% deviations.

This may make a considerable difference as to how the noise effects are reduced. To a certain extent, the reduction of the effects will also depend on which measurement is being taken. For Auger mapping, where signal-to-noise ratios are generally less than 10:1 per pixel, the ratio technique used for topography suppression is quite good. This is also true for line scans if the noise bandwidth is smaller than the sampling bandwidth. For spectroscopy the detection of dN(E)/dE reduces the effects of flicker noise considerabley, Pocker and Haas (1975), Todokoro et al. (1981), Todd and Poppa (1979). Again, the high frequency modulation is normally above the noise frequency. The flicker noise can be further reduced by normalizing the dN(E)/dE signal with the N(E) signal, Janssen et al. (1977). However, the use of dN(E)/dE is attended by a loss of signal and consequently an increase in the relative shot noise, Frank and Vasina (1979). In microscopy, it is preferable to have another source of normalization, such as the sample current, the secondary SEM signal, or current from an intermediate splash anode in the electron column, Bishop (1977), Browning et al. (1977), Zironi and Poppa (1981) and use the direct N(E) spectrum acquisition.

The lower frequency (310) cold field emission noise appears easier to treat than the higher frequency (100) emission noise, even though the total changes can be larger. The (310) noise can be reduced considerably applying stringent vacuum conditions, Todokoro et al. (1981), and with lower frequencies the sampling of the beam current is less problematic. For (100) thermally assisted emission this author has found that sampling the beam current slower than 200 Hz, using an analog-to-digital converter, introduces out-of-phase noise when used for normalizing N(E) spectra, and is therefore not at all useful. Either many beam current samples must be taken at a higher sampling rate or an integrating method must be used.

Residual noise from beam fluctuation and other sources such as vibration and pickup can be reduced by averaging spectra over many scans, this being a very common method used with digital acquisition.

Shot Noise

Shot noise is a fundamental limit to signal measurement accuracy. Its consideration is particularly important in the Auger microprobe because of the low cross section for the generation of Auger electrons and the presence of a large secondary electron background. Shot noise originates in the random uncorrelated arrival of electrons at the detector over a finite sampling period. This process can be described by Poisson statistics, and the shot noise is then proportional to the square root of the average sampled count. If we can consider detecting N_A electrons originating from an Auger transition and N_B Electrons originating from the unstructured background over a counting period, and if we take two samples, one on an Auger peak, and one off the Auger peak to determine the Auger signal, (c.f. Fig. 1), then the signal-to-noise ratio in the measurement will be:

$$S/N \approx N_A/(N_A + 2N_B)^{\frac{1}{2}} \qquad (1)$$

As background counts are from 5 to 10 times as great as Auger counts, then even a modest signal to noise ratio of 10:1 requires $N_A \approx 10^3$ counts. (This result assumes an energy dispersive analyzer). To give some typical but order of magnitude figures: with 1nA beam current, a near monolayer of oxygen, detected with a CMA of 1% resolution, a 100 ms sampling period would be required. This would imply nearly

two minutes for a 1000 eV spectra in 1 eV steps. If a 1% measurement accuracy of multiple peak heights were required, hours of acquisition would be necessary. Ignoring any questions of beam damage from such long exposures, if high spatial resolution point spectrometry were used, the spatial resolution would depend entirely on the mechanical stability of the stage, the long-term drifts in the column, and electronic stability. It is difficult to put an exact figure on these drifts in the typical Auger microprobe as they are not normally quoted, and there are both long and short term drifts in a stage relaxing after movement. It is very possible that the spatial resolution in many systems is actually limited by this, rather than the probe size for point spectrometry. It is clearly important to keep to a minimum the time required for analysis of a point spectrum, and this will mean extracting signal from noisy spectra.

The time needed for acquisition can be reduced considerably by using smoothing and integration of peaks. Some of the smoothing methods suitable for Auger spectra have been reviewed by Yu et al. (1982). The easiest of these methods to implement is described by Savitsky and Golay (1964). Their method is based on a least squares fit of n points to the data, which reduces to weighting n points with a Gaussian and averaging. For a small number of points in the weighted average this is an attractively simple smoothing routine, and computationally efficient. But if lower frequency noise is to be removed the computation becomes less efficient and time consuming. For lower frequency noise either spline fitting, Reinsch (1967), or fast Fourier transform techniques are used, Kosarev and Pantos (1983). Fourier transform techniques have the advantage of utility in other processing such as differentiation and integration, Keenan and McGuire (1977). Further, a fast Fourier transform routine is relatively simple to program, 20 to 30 lines of FORTRAN or BASIC, and these are often available as library routines. The signal-to-noise ratio can be further improved by subtracting the background and integrating the Auger peak, Hesse et al. (1976), Kirschner (1979), but this is not particularly straightforward. There are several techniques that have been applied to the background stripping. Spline fitting, Hesse et al. (1976), loss feature deconvolution, Madden and Houston (1976), and the linearized cascade technique of Sickafus (1977a,b), and finally using the loss feature model of Shirley (1972), Sickafus (1980).

Matrix Effects

Matrix effects such as backscattering inhomogeneities and mean free path differences are contrast mechanisms that may be significant in some applications. Variations in backscattering from inhomogeneous subsurface atomic number distributions, give contrast in Auger yield that are not related to the surface elemental distribution, Harris (1974), Kirschner (1976), and variation in mean free paths from near surface distributions will alter the apparent yields, Seah and Dench (1979). The treatment of these complex mechanisms in imaging is somewhat speculative at present. To a first approximation the yield variation from backscattering appears to be a function of the average atomic number in the scattering volume, which will make the problem more tractable, Ichimura and Shimizu (1981). Bishop (1982) has suggested that there is a possibility of using the higher energy background electrons $\sim$2 keV as a normalization for both topography and atomic number contrast. The shape of the background distribution is not markedly different for a change in angle of incidence and high energy background is not sensitive to atomic number. He suggests that, by comparing Auger/background ratios from standard surface compositions, the unknown may be found just using a single peak. Another option is color normalization, as it appears that the ratio of sensitivity factors is less variable with matrix effects, Hall et al. (1977). With widely differing Auger energies and substrate compositions a simple approach is likely to fail and more information may be needed from the sample such as the x-ray microprobe signal, Kirschner (1979), or the backscattered electron signal, Thomas (1983).

General Considerations for Computerization

It is clear from the preceding summaries of the Auger microprobe signal characteristics that the computer will be applied to a wide range of tasks. It is also clear that the beam/sample interaction is still being researched and that the data reduction techniques are in a process of evolution. This implies two things about the hardware and software, particularly the software. Firstly, it will be complex, and secondly, it will be continually modified. As the source code could well be many thousands of lines, this is a very unfriendly software environment. Unnecessary complexity of hardware and software must therefore be kept to a minimum while at the same time the system must have forward looking flexibility. The software is the more critical problem area, as the ratio of software development time to hardware development time is unlikely to be less than five to one.

The tasks of a computerized Auger acquisition system fall into two main areas, quantification of spectra and image processing. The quantification of spectra using computer techniques and N(E) spectra has been shown to be a great advance over analog methods. This has been made possible because a local standards data base can be set up, and a close definition of experimental operating conditions can be enacted. This must be a primary aim of any computerized system. For work on poorly defined and rough samples, spectra are not sufficient. On such samples imaging is vital to give information that is

characteristic of the sample, not the sampling positions. To do this, novel techniques for image collection, processing, and display are needed. In general the main technique used at present is a point-by-point background normalization with a single Auger peak acquired and displayed. Auger images are therefore often not very meaningful. This is not only because of the problem with contrast mechanisms, but also because Auger images have an ill defined relationship with other data. Several improvements can be made to imaging techniques with a little speculation. Collection of simultaneous multiple images and a higher resolution SEM image would add synergistically to the information presented either in false colour images or mixed images. This approach would also provide an alternative topographic and self consistent normalization scheme. Collection of multiple backscattered images for depth profile calculation and atomic number contrast measurement could be valuable, while measurement of instantaneous incident angle would be usable in an additional correction for topography. Other information in the background, at high and low energies, will provide further insight into the beam/sample interaction. Clearly in designing a computer system for Auger imaging the use of novel techniques must be allowed for.

Software

The software is the most critical element in any computerized design for Auger microscopy. The many routines needed to interactively control the microscope, collect the data, and then reduce and present that data, imply a large software suite and several man-years of effort. Any approach to the software is therefore a most important judgement area. One approach is to use existing programs, but the varied requirements within the surface microscopy field have allowed very little collaboration and sharing of software. This, in part, is also due to the incompatibility of software run on different computers. There are also few guidelines, even to which language would be most appropriate, both for present use and in the near future. It is extremely difficult to quantify such variables as, utility, ease of programming, and flexibility of a language and its relationship to a particular problem area. For image processing, FORTRAN appears to be the language of choice. FORTRAN has the advantages of portability, high level, and the inbuilt speed of a compiled language. For data collection FORTRAN is not so suitable and it is often necessary for reasons of speed to code portions of the programs dealing with input, output, and disk-file handling in assembly language, Shaffner and Keenan (1979), Jones and Unitt (1980). With the wider dissemination of C as a programming language this task could be largely taken over by a higher level language, but it is still a necessity to have an intimate knowledge of the operating system, Fisher and Cone (1982). Basic is generally considered to be a very poor language for writing lengthy programs. However, more recent BASIC dialects have been written, that, if used with care, can satisfy many of the requirements for modular and structured programs that are normally considered the province of PASCAL or C. BASIC, being an interactive language, is also particularly suitable for control of instrumentation and this approach has been used by several groups, Prutton and Peacock (1982), Bishop (1980). This author has also used the Hewlett-Packard BASIC programs described by Prutton and Peacock (1982) as a basis for a new program suite. Unfortunately these programs are not portable from the computer series that they were written for. The movement towards generic UNIX operating systems for small computers may conceivably make programs more portable, Warren (1983). PASCAL or C would then be the language of choice, but this would be at the expense of the line interpretive facility of BASIC which is of great value in operating hardware and in rapidly implementing new ideas. The duplication in effort seems likely to continue for some time to come, but equally a major concern must be that an individual groups investment in software is not wasted as both computer and microscope hardware changes.

Conclusion

The requirements for computer control of surface physics microscopes are changing as new techniques are evolving. New computer technology is keeping pace with the requirements for memory size, data storage, and computation speed. The onus is now on the programmer to produce well written software with a long life cycle. The lack of portability of programs is a serious drawback to efficent use of resources within the field. As the impact of software complexity becomes apparent the difficulties in implementing a new system may well have some negative effect on innovation. However the computerization of surface microscopy has made possible considerable gains in measurement accuracy and understanding of the technique. Many novel methods are possible with computer controlled instrumentation and systems should be designed with this as an integral aim.

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Discussion With Reviewers

H. E. Bishop: I feel that the subject of computer control in AES has been rather neglected in the literature considering its widespread use, in particular the user-machine interaction. Commercial software is often very impressive at first sight but, as you have pointed out, can prove very restrictive. Do you think it would be possible for the Auger community to draw up a general specification for AES data systems as a guide to manufacturers and as a standard against which a given system may be compared?

Author: I certainly think that a general specification for an AES data system would be valuable if one could be written. In both the hardware and software there are aspects that could be generalized. I think access to software is one such area and design of the system/computer interface another. The software is the most important and will be the most difficult to specify. The construction of software around well engineered modules, a tool box approach, would allow high level access and a great deal of flexibility without compromising commercial interests. The separation of data collection, manipulation, and presentation from the system control would allow this to be done safely, even in highly automated systems. Portability of software is also important however, and a standard would have to be decided on. At present this would be a very difficult criteria to meet because the computer industry has no real standard for small computer systems. Alternatively, as I believe you have done, one could specify the hardware/data system interface and leave the computation options open, where the line is drawn could be quite flexible. However there is a wide disparity of user needs and approaches so there may be a problem in going much further than quite general and therefore not very useful requirements. As you point out the subject has been neglected and there may be many common options that should be drawn up as a specification.

T. J. Shaffner: Would not a background correction scheme based on area, rather than single channel height as in Fig 1, be considerably more accurate? What work has been reported based on area measurements?

Author: It would be more accurate to use the area of peaks, that could be separated, for an estimate of the Auger yield. I don't know whether this would significantly improve the normalization against topography using just one peak. The use of a single channel is a pragmatic approach for use in line scans and imaging with the advantage of being a limited but self consistent data set. I know of no publications that have used the Sickafus (1980) methodology to investigate this problem, and I would assume that this approach would be necessary to fix the limits of accuracy.

T. J. Shaffner: You make reference to past and current work with field emission sources, but have not mentioned the constraints imposed on these systems by specimen damage. Would not the S/N advantage gained by field emission be offset by the real probability that outer monolayers of the specimen have been ruptured by such high electron fluxs (up to 1000 amp/cm^2)?

Author: It is true that some specimens will be damaged, but apart from heating effects, I believe that most effects are dose, not dose rate, dependent. So there is no advantage in not having good signal to noise at high spatial resolution. This allows one to make a trade off between spatial resolution and signal to noise on such samples.

Ref 3

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A novel histogram technique to obtain chemical information near maximum spatial resolution in a SAM

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1. Introduction

Scanning Auger electron microscopes (SAM) can produce maps of the distribution of a chemical element on a surface with a lateral resolution of 100 nm or less. However, the chemical composition of surface regions with a size comparable to the measured resolution of a particular SAM cannot be readily ascertained. Even if the specimen manipulator and beam deflectors allow the probe to be positioned on a small region of interest, it is often impossible to collect point spectra from such a region because of drift of the specimen stage relative to the electron column. Spectra collected whilst deliberately rastering the electron probe over an area of the surface encompassing both a small region of interest and the surrounding regions do not enable the composition of the small region to be found directly and, if the region forms only a small proportion of the total scanned surface area, its contribution to the spectrum may be obscured by statistical noise. Drift of the stage can also prevent the repeated averaging of spectra, linescans and images in order to improve the SNR and this may preclude the determination of chemical composition to the desired degree of accuracy. If the elemental concentration from region to region of the surface differs by less than 10 a/o dwell times of the order of 200 ms per pixel are generally necessary and a chemical map of 128 x 128 pixels will take ca 55 minutes to collect. Furthermore, if the surface is chemically inhomogeneous on a scale comparable to one inter-pixel spacing, the pixel-to-pixel intensity variation might be mistakenly ascribed to statistical noise and would be obliterated by any subsequent spatial averaging of the image array.

The purpose of this paper is to describe a "composition histogram" technique which can be used to overcome some of the problems alluded to above. It enables the gathering of surface chemical information near the maximum spatial resolution in a SAM despite drift and fluctuations in the beam current. Examples of experimental results obtained using this technique are presented and their interpretation is discussed.

2. The Histogram Technique

The collection of composition histograms is most easily accomplished if a digital computer controls the SAM as is the case at York (Prutton et al 1982). Auger images are obtained by stepping the electron probe across the specimen surface and acquiring two pulse-counted N(E) signals at each point: N1 at the energy E1 of the Auger peak and N2 on the background at E2

just above the peak in energy. A composition histogram is also collected while stepping the probe across the surface, either in a raster or random pattern, but for each point the heights of two Auger peaks are sampled. The ratio of peak heights is used to construct a histogram of number of points (vertical axis) versus peak height ratio. The position of the probe when a particular ratio is obtained is not stored but the number of pixels present within each column of a histogram depends upon the proportion of the total frame scan area which has a composition within the range of ratios defined by the column width.

During the acquisition of composition histograms at York, N1, N2 and the SEM signal S are acccumulated simultaneously for each point of in image line and, on a second scan of the same line, N3 and N4 for a second Auger peak are acquired along with the SEM signal S'. It is assumed that the specimen does not drift by an appreciable amount in the time taken for one image line. For each point the peak height ratio is calculated using

$$R = \frac{N1-N2}{N3-N4} \times \frac{S'}{S} \qquad (1)$$

The term S'/S compensates for any change in beam current which may have taken place between the two line scans. No further normalisation is required if it is assumed that both Auger peak heights have the same dependence upon surface topography and that diffraction effects are absent. An assembly language subprogram controls the SAM during histogram collection and updates a display of the histogram as the data are acquired. The provision of this real-time display allows the user to assess the histogram SNR and terminate acquisition when it is judged to be acceptable. For the histograms presented in the next section, N1, N2, N3 and N4 were each accumulated for 100 ms at every point of a 64 x 64 point array. The time taken to collect a histogram was therefore half that required for a single 128 x 128 pixel image (200 ms per pixel).

3. Results and Interpretation of Composition Histograms

A histogram obtained from an Al specimen after exposure to 3000 L of oxygen is shown in Fig 1. Values of R were obtained by dividing the Al LVV signal by the O (510eV) KLL peak height, the energies of these features having been measured from N(E) spectra. The Al peak (sampled at an energy of 60 eV for the histogram) resulted from a superposition of the Al (65 eV) LVV peak and the chemically shifted Al(Al_2O_3) peak near 50 eV. One large feature dominates the composition histogram (Fig 1) and its maximum lies near the ratio R=20 expected from the peak heights in the spectra. From spectra, the expected ratio for specimen regions devoid of oxygen is ca 123 and a small peak does appear in the histogram near this value of R. If the measured peak height at 510 eV were to decrease, the value of R would increase. However, statistical fluctuations might cause N4 to exceed N3 giving negative values of R. Broad features in the negative region of the histogram are visible in Fig 1. Although the origins of some of the peaks are unknown, this histogram clearly demonstrates that the Al has been oxidised non-uniformly on a scale at least as great as the SAM spatial resolution. Such a conclusion could not have been drawn from images obtained from this specimen and point spectra could be very misleading in such situations.

A more easily interpreted histogram, from a surface of clean Ag, is shown in Fig 2a for the ratio of O(510 eV)KLL to Ag(353eV)MNN peak heights. By its comparative simplicity this figure demonstrates that the many features of Fig 1 were not artefacts of the collection system but were related to

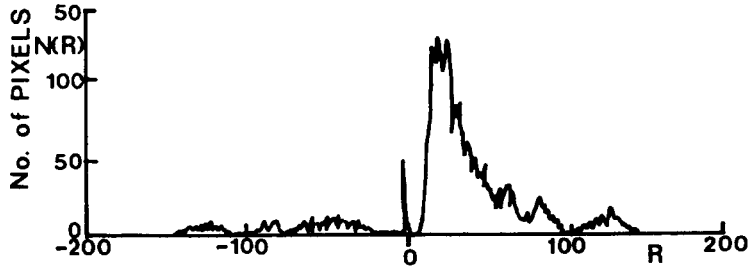

Fig.1 An histogram (Al/O) from partially oxidised Al

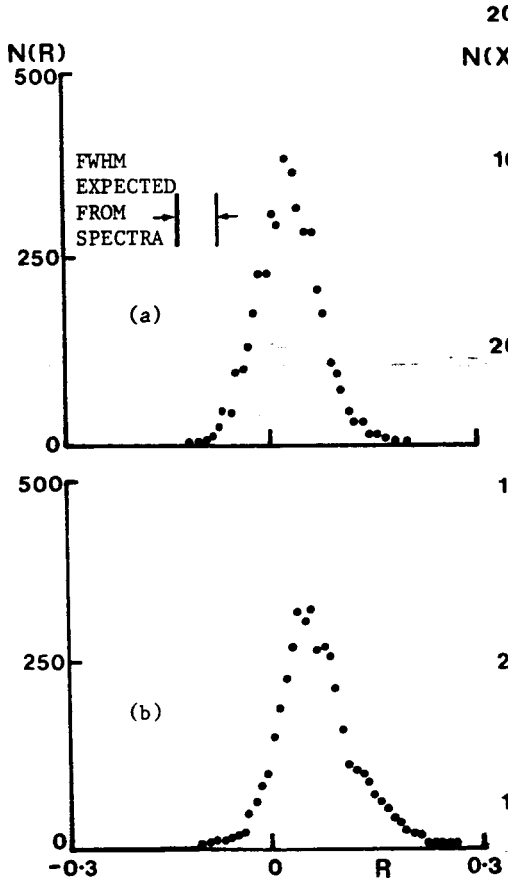

Fig.2 Histograms (O/Ag) from
(a) clean Ag;
(b) around a particle on the same surface

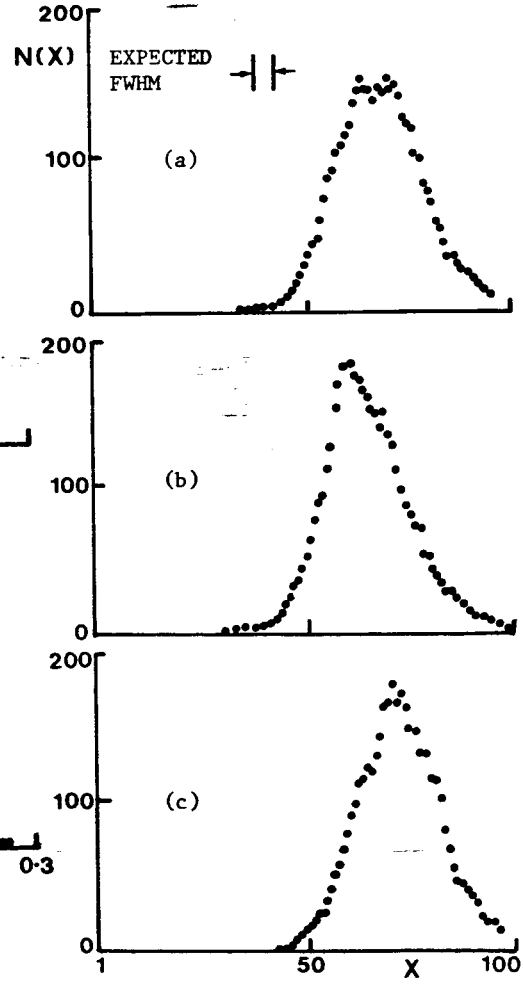

Fig.3 Histograms from (a) an 80 x 112 μm area of a NiCrAl alloy and from two different regions (b and c) within the same area

the nature of the specimen surface. The scan area used in the histogram of Fig 2a appeared to be featureless in an SEM image. However, an adjacent region contained a particle several microns across. A spectrum from this particle showed that it was composed of Ag but also exhibited a small oxygen signal. A histogram (Fig 2b) obtained from a specimen region encompassing the particle exhibits a shoulder on the side of the main peak where no such shoulder is present in Fig 2a. From spectra, the ratio of O/Ag peak heights was expected to be 0.06 for clean Ag and 0.12 for the particle. Similar ratios were measured using the peak positions in Fig 2. R in this case was calculated by dividing a small peak height (N1-N2), which can be expected to have a Gaussian noise distribution, by a large peak height (N3-N4), for which the SNR is much greater. If the much smaller noise contribution of the large peak is neglected, the histogram peak shape is expected to be Gaussian. The measured width of the approximately Gaussian peak of Fig 2a is in close agreement with the FWHM (full-width at half-maximum) calculated from the spectral signal-to-noise ratios. However, if a large peak height is divided by a much smaller peak height to give R, the observed histogram profile is asymmetric as can be seen from Fig 1.

The width of peaks in histogram plots is sometimes greater than anticipated from an examination of SNR's in spectra as in the case of Fig 3a which was obtained from an etched Ni-Cr-Al alloy surface (El Gomati et al, 1983). To assist in the interpretation of the histogram of Fig 3a, it has been replotted on a linear scale where the horizontal axis value for a histogram point of ratio R is given by

$$X = 100/(1+R) \qquad (2)$$

Although the result of equation (2) is plotted on a scale X = 0 to 100 this must not be taken as referring to percentage concentration. R has not been corrected to allow for differing elemental sensitivities and matrix effects and the ratio of only two peak heights (Cr(527 eV)/Ni(844 eV)) is displayed for the ternary alloy. Fig 3a appears to be double peaked implying that at least two regions of differing composition have contributed to the plot. Auger images of the same surface also showed that two distinct surface phases were present in regions ca 20 μm across. Histograms from within the boundaries of each of these phases are shown in Figs 3b and 3c which exhibit maxima for different values of X. Fig 3a can be synthesised to a good approximation by a weighted addition of 3b and 3c where the weightings are in accordance with the areas occupied by each phase in the scanned area of Fig 3a. Figs 3b and 3c are both broader than expected from noise arguments alone implying that there is a spread of compositions within each phase. In addition, each of these histograms consists of a main peak with a shoulder. Auger imaging has confirmed that within each surface phase boundary two distinct regions (less than 2 μm across) of differing composition are present.

In conclusion, the method of composition histograms has been used successfully in a number of cases and is already proving to be a powerful microanalysis technique. If is of particular use in quickly establishing how many regions of differing composition are present on a surface and, because it is independent of drift, data acquisition can be continued until the desired SNR is attained.

References

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Prutton M, Browning R, El Gomati M M, Peacock D C 1982 Vacuum TAIP 32 351